SCIENCE

CONTENTS

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THE STUDY OF IGNEOUS ROCKS [1]

No branch of petrology presents so attractive a field for investigation and study as that concerned with the origin and formation of igneous rocks. The great problems of metamorphism that traverse so much of the earth's dynamic history and involve so many factors common to the problems of igneous rocks are less alluring because of their greater complexity, and less definite character. While much is being done in each of these fields of rock study, it is to the former that I wish to call attention at this time. It is interesting to note how the attitude of the petrographer toward the subject of igneous rocks has changed with increasing knowledge of their composition, and with advancing experience with the fundamental laws of physics and chemistry.

Rocks that were considered igneous a century ago were almost wholly those known to have poured forth from volcanic craters, and were, for the most part, compact, aphanitic lavas, often containing porphyritic crystals—distinctly volcanic rocks. The great number of phanerocrystalline massive rocks were not generally considered as having the same character and origin as volcanic rocks, as being igneous. Their formation was explained in different ways by various geologists. And when treated

[1] Address of the vice-president and chairman of Section E—Geology and Geography—American Association for the Advancement of Science, Baltimore, 1908.

as "plutonic," were still thought of as different from "volcanic" rocks. Some of the commonest were considered as extreme forms of metamorphism, and have been so treated until quite recent times by eminent geologists.

Not only the geological mode of occurrence of many of these rocks was unknown, or only partially known, but the inherent, material characters were often matters of conjecture. Before the introduction of the microscope by Sorby, in 1850, the mineralogical study was confined to the larger, megascopic crystals, except for the microscopical investigation of rock fragments and powder by Cordier in the first decade of the last century. And the early chemical analysis of rocks, while adding considerably to a knowledge of their composition as a whole, lacked the completeness and accuracy of modern analytical methods, and failed to explain the composition of the rocks because of the absence of satisfactory knowledge of the mineral components.

With improved methods of investigation, geological, mineralogical and chemical, knowledge of the character and composition of rocks advanced. The supposed distinction between "volcanic" and "plutonic" broke down, or assumed new definition, through the observations and writings of Judd and others. The term "igneous rocks" came into more general use, and embraced all "volcanic" and "plutonic" masses. The mineral composition of all crystallized igneous rocks became known in more and more exact terms, though much remains at present to be learned of the definite chemical composition of some of the common mineral components of most rocks. Chemical analyses of rocks are becoming more complete, and more frequent in petrographical publications, and the store of chemical data is steadily increasing and has been made more available by the collec-

tions of rock analyses published by Roth and more recently by Washington.

The description of igneous rocks has been largely fortuitous. As rocks happen to have been encountered in geological field work, they were collected, and not always with due regard to their geological relations to other rock bodies; and subsequently they were investigated in the laboratory, more or less thoroughly, and described, often very imperfectly. Up to recent times the terms "petrography" and "petrographer" applied satisfactorily to the subject and to the worker in it, for the work was chiefly descriptive.

Generalizations regarding the nature of igneous rocks, or the formulation of laws controlling their crystallization, were largely empirical dicta not infrequently based on incomplete knowledge or inadequate experience. As a natural consequence of the haphazard manner of growth of the science, there has been an unsystematic nomenclature, derived from many sources at widely remote times, expressing markedly different degrees of information regarding the thing described—rock, texture or relationship—and in many instances representing in a single term a series of definitions varying with shifting opinion or advancing knowledge. Such, for example, as syenite, granite and trachyte.

At the present time attempts are being made to apply to the study of igneous rocks the results of laboratory experience in physical chemistry and, not only to investigate directly the physical behavior of molten rock minerals singly and in combinations, or mixtures, but to apply the more advanced laws of physicochemical reactions to the elucidation of the problems of crystallization, differentiation and mineral composition. The researches of Day and his colleagues in the geophysical laboratory of the Carnegie Institution of Washington, D. C., upon temperatures of

fusion, crystallization, and transformation points of silicate compounds corresponding to rock minerals, and of the behavior of mixtures of pairs of such compounds in producing mixed crystals, new compounds or eutectic mixtures, are of the first importance. The accuracy of the methods employed and the thoroughness of the work guarantee the value of the results and their permanency. In addition to the establishment of improved, or entirely new, methods of operation of a purely physical character tributary to the study of petrological problems, they have determined the isomorphism and physical behavior of the lime-soda-feldspar series; the relations of the various lime-silica compounds to one another; those of the lime-magnesia-metasilicate series; the melting and transition points of quartz and tridymite, and the character of still other compounds, and they have materially extended our knowledge of solid solutions.

Doelter and his pupils have studied the fusibility of the rock minerals and their solubility in one another, but the methods employed are less accurate than those just mentioned and involve a large element of subjectivity. They are approximations to the facts desired, often of much value qualitatively, but sometimes misleading. Other recent and valuable qualitative work in this field has been done by Morozewicz, while earlier work is represented by the classic researches of Daubrée, Fouqué, Michel-Lévy and others.

The most obvious result of the earlier efforts was the demonstration of the adequacy of fusion and gradual cooling, at ordinary atmospheric pressures, to bring about the crystallization of many minerals found in igneous rocks; and the necessity of some catalytic agency to promote the crystallization of other minerals common to these rocks. Such actions were ascribed to "mineralizing agents," or "crystallizers," assumed to be in most instances dissolved gases, chiefly H_2O. One of the most significant facts brought to light by the researches of Day and his colleagues is the new conception of high viscosity found in alkali-feldspars and quartz. Viscosities so great at temperatures near the transition point of liquid to crystal phase as to be indistinguishable within the two phases. That is, the viscosities of the amorphous glass and of the crystallized mineral are so nearly identical that the two phases of the substance react alike toward mechanical stress. Molecular mobility is so slight that readjustment from crystalline arrangement to the homogeneous chaos of liquid molecules is accomplished with such extreme slowness that the time of ordinary laboratory observation is not sufficient for its detection. However, the time available for ordinary "geological" processes, so called, is sufficient, as shown by the devitrification of volcanic glasses composed of these constituents—ancient rhyolitic obsidians. The function of a catalytic agent, as a gas dissolved in such a viscous liquid, is obvious—the viscosity is reduced and molecular mobility increased. If the transition is toward the liquid phase, solubility of the crystal is increased. If it is toward the crystal phase, the rate at which crystallographic molecular arrangement is accomplished is increased. The dissolved gas becomes a "crystallizer," or "mineralizing agent." Other substances, such as mineral compounds, yielding less viscous liquids than those of the alkali-feldspars and quartz, when dissolved in the more viscous liquids, reduce their viscosity in the same manner, though not to the same extent, as dissolved gases. They must behave catalytically toward crystallization, as gases do. Their behavior in this respect has not been generally recognized, though the function of certain liquid compounds, as fluxes, or as "mineralizing agents," is well known.

Thus the improvement in methods of

physical research is steadily enlarging the field of petrological investigation, and the advancement in the knowledge of physico-chemical laws is furnishing the investigator with new tools for the work and more efficient means for attacking the problems of igneous rocks. Foremost in the ranks of those who have attempted the application of modern conceptions of physical chemistry to the elucidation of the phenomena of texture and mineral composition and of the genetic relationships of igneous rocks is Vogt, whose earlier studies of furnace slags opened the way for the explanation of many analogous phenomena in the more refractory, volcanic lavas. Chief among these are the apparent order of crystallization of different minerals in slags, as indicated by their shapes and relations to one another as inclusions, and the relation between these orders and the composition of the mixture from which they crystallized. Vogt's observations were found to be in accord with modern theories of solutions, as Bunsen foretold in 1861, when he affirmed his belief that rock magmas are solutions of silicate compounds liquid at high temperatures. Vogt has called the attention of petrologists to these modern theories as developed by Arrhenius, van't Hoff, Ostwald, Gibbs, Meyerhoffer, Roozeboom and others. He has also made definite application of them to some of the phenomena and relationships mentioned. His publications have extended widely the horizon of modern petrology, which by the assumption of these broader, deeper phases of the study of igneous rocks, and of similar problems affecting metamorphic rocks, has passed beyond the narrower boundary of petrography, strictly so called.

The evolution of chemistry from a state of pure empiricism to one of comparatively logical sequence has placed before us a collection of coordinated laws, which, while incomplete, or subject to numerous exceptions, furnishes us with means to postulate reactions between the constituent elements of rock magmas with reasonable assurance of correctness, or to explain the formation of mineral compounds hitherto in a measure enigmatical. Much remains to be more firmly established, both as to the chemical character of the elements and their compounds, and with regard to theories relating to their reactions, and even to the very nature of their existence in some instances. The silicate compounds constituting igneous rocks remain largely uninvestigated, so far as concerns their synthesis and reactions in mutual solution. And the physical study of solutions and of their transitions to the solidified components—especially the more complex mixtures—is far from completed. The present is a period of transition in the development of petrology, as were also times past. But the changes taking place at this time appear to be so many and so fundamental that it may well be asked whether the older methods of approach to the study of igneous rocks should not be replaced by others more in accord with present conditions of knowledge of chemistry, physics and of the rocks themselves. The older method, in the nature of things, was, and is largely at the present day, objective, and the expressions of relationships or laws empirical.

It would seem more reasonable to begin a systematic study of igneous rocks with a consideration: of the most fundamental characteristics of the magmas from which they have solidified; of their constituents, together with their probable chemical reactions and the resulting mineral compounds; of the manner in which these may separate from a silicate solution, or rock magma; of the shapes they are likely to assume upon crystallization and the consequent texture of the rock. Processes of molecular separation of magmas lead to the discussion of the differentiation of magma into chem-

ically unlike parts and the resulting different varieties of igneous rocks, together with their eruption and solidification as geological bodies of various kinds.

Assuming a certain elementary acquaintance with rocks on the part of the student, which is acquired in courses in general geology, the systematic treatment of the subject should begin by calling attention to the chemical composition of unaltered igneous rock as shown by analyses, published in many descriptions of rocks, but most conveniently found in comprehensive collections in Bulletins of the U. S. Geological Survey and in the tables of analyses edited by Justus Roth and more recently by H. S. Washington. The extremely variable nature of these data and their great abundance present such an exceedingly complex set of numerical relations that their statement, or discussion, requires the aid of diagrams by which the problem may be greatly simplified.

In addition to the chemical elements noted in ordinary rock analyses there is a much greater number known to occur in rare minerals that crystallize from rock magmas in special instances, or that oftener appear in certain varieties of igneous rocks, such as the pegmatites. A consideration of all known pyrogenetic minerals with respect to their chemical composition calls attention to the compounds that are repeatedly formed in igneous magmas by the union of the elements that existed in the magmas before their solidification. And by arranging them in accordance with the order of their constituent elements in the Mendeléeff series valuable information as to certain chemical relationships among these compounds is at once furnished.

The substances occurring in igneous rocks are in most cases solids, less often liquids or gases. The solid compounds are always in crystallized condition. Amorphous, glassy solids that sometimes occur in igneous rocks are seldom, if ever, definite chemical compounds, but are mixtures. The crystallized substances (minerals) are rarely present as uncombined elements, such as gold, graphite and metallic iron. A few are simple compounds with invariable composition, as SiO_2 (quartz), TiO_2 (rutile), Al_2O_3 (corundum). Most of them are complex and variable in composition, owing to the presence of isomorphous mixtures, as the feldspars, olivine, amphiboles. There are very few examples of polymorphism, such as quartz and tridymite. The apparent difference in the crystallization of orthoclase and microcline is probably due to submicroscopic multiple twinning in the apparently more symmetrical form. Polymorphism of some of the pyrogenetic compounds, as $MgSiO_3$ and $CaSiO_3$, which is known in laboratory products is not clearly developed in pyrogenetic minerals.

Certain isomorphous mineral compounds are not developed in igneous magmas with like frequency, or in certain cases not at all. Such, for example, are the hexagonal compounds $NaAlSiO_4$ (sodium-nephelite), $KAlSiO_4$ (kaliophilite), $LiAlSiO_4$ (eucryptite). Compare also the potash-, lithia- and soda-micas. Other compounds that are analogous chemically and might be expected to crystallize isomorphously in igneous magmas have quite different crystal symmetry, as is the case with $KAl(SiO_3)_2$ (leucite), $NaAl(SiO_3)_2$ (jadeite), $LiAl(SiO_3)_2$ (spodumene).

Various silicate compounds involving different silicic acids: orthosilicic, metasilicic, polysilicic and in rare instances disilicic, besides uncombined silica, may crystallize from the same rock magma. And even base-forming elements, as iron and aluminium, may, under some conditions, separate from rock magmas as oxides without combining with silica, which may itself separate as SiO_2. That is, hematite, magnetite or corundum may crystallize in the pres-

ence of quartz. On the other hand, certain lower silicates do not form when there is sufficient silica to form higher silicates with the same bases. Thus $KAl(SiO_3)_2$ (leucite) and $NaAlSiO_4$ (nephelite) do not occur pyrogenetically with SiO_2 (quartz).

Moreover, it is well known that some rock magmas, especially those of intermediate composition, crystallize under one set of conditions into certain combinations of minerals, and under others into other combinations, certain minerals appearing in one case and not in another, though the magmas from which they formed were chemically alike.

In order to account for the production of the mineral compounds known to occur in igneous rocks, as well as for the absence of others; and to understand the possibility of variation in the production of mineral compounds from any magma under variable conditions; and to comprehend the act of separation and crystallization of such minerals upon the solidification of the magma; it is necessary to consider the probable physical and chemical character of liquid rock magmas, especially the known physicochemical laws regarding solutions.

Discussions of the behavior of solutions under varying conditions of temperature and pressure involve theories of the possible molecular constitution of matter, gaseous, liquid and solid, which must be kept in mind in order to form any clear conception of the processes under consideration. The kinetic theory regarding the behavior of molecules of gas, liquid or solid, under variable temperatures and pressures, furnishes definite pictures of changes of state at transition points from one phase to another. Those with which the problems before us are most concerned are the critical point of gases, the melting point of solids, the solution or the separation points of solids in liquids and also the

transition point between two crystal phases of the same compound (such as that between quartz and tridymite).

Since liquid rock magmas are solutions of silicate compounds in one another, all that is known of the physical and chemical behavior of solutions is germane to the discussion. This includes the solution of gases, liquids and solids, in liquids; and eventually their solution in solids; the solubility of various substances in liquids of other substances; the possible molecular constitution of liquid solutions; the existence of molecules of different degrees of complexity, and the dissociation or ionization of some compound molecules; the laws relating to diffusion, and the relative diffusibility of various compounds; those relating to the molecular concentration—the saturation and supersaturation of solutions. The chief qualifying factors in this discussion are the chemical composition of the several compounds; the possibility of changes in chemical equilibria; the viscosity of the solution; the temperature, pressure and the time through which any operation acts. The possibility of producing in a colloidal condition one of the compounds, $Al(OH)_3$, $Fe(OH)_3$ or $Si(OH)_4$, by the interaction of the hydroxyl (OH) and aluminium (Al), iron (Fe), or silicon (Si), is also to be taken into consideration.

In a solution containing the chemical elements common to igneous rocks reactions should take place between them in accordance with known chemical laws, and with results corresponding to observed pyrogenetic mineral compounds. Some of the fundamental laws relating to chemical reactions among the elements are based upon conceptions of chemical energy and activity, and of the conditions that modify their effects. An important factor in chemical processes is, often, a catalytic agent that promotes reactions without itself appearing as a component of the final products. The

chemical behavior of ionic substances, and especially the hydrolyzing action of ionized water, are other factors in the problem under consideration. The relative strength of chemical activity in the base-forming, or acid-forming, elements, and their ability to form acids and salts, lead to the discussion of the production of the pyrogenetic minerals from liquid magmas composed of elements found in igneous rocks; some of these minerals having been produced in the laboratory by melting together the component elements in proper proportions.

Considering what should take place in a solution having the composition of an average of all igneous rocks, it can be shown, since the chief acid-forming elements present are silicon in large amount, and the more active element phosphorus in very small amount, that salts with these elements in the acid radical must be common. Other acid-forming elements occurring in small amounts are titanium and zirconium; while iron and aluminium may play this rôle under favorable conditions. The more active, phosphoric, acid forms unstable salts with the active base-forming metals, potassium and sodium, but a very stable compound with the less active metal, calcium, into which compound fluorine, or chlorine, enters; yielding apatite, an almost universal component of igneous rocks.

Silicon is known in the laboratory to form one definite acid, H_4SiO_4, orthosilicic acid; and other acids of silicon have not been isolated and identified. But very definite mineral compounds exist that indicate that salts from other silicic acids form under proper conditions. These are:

H_4SiO_4, orthosilicic acid;
H_2SiO_3, metasilicic acid;
$H_4Si_3O_8$, polysilicic acid;
$H_2Si_2O_5$, disilicic acid.

It is significant that in laboratory experience with orthosilicic acid, H_4SiO_4, prepared from aqueous solutions, the com-

pound may be made to lose water gradually until nothing but silica, SiO_2, remains. In this way free silica may be separated from a silicate compound, a hydrogen silicate; since an acid may be considered as a hydrogen salt.

Observations upon the pyrogenetic minerals, and laboratory experience with synthetical operations, show that salts of several kinds of silicic acids form by the side of one another, and that their character and amount depend on the nature of the base-forming elements present in the mixed solution. Orthosilicates, metasilicates and polysilicates commonly form in the presence of one another, sometimes accompanied by uncombined silica. And it becomes more and more evident that the formation of the different kinds of silicic acid ions, or their salts, is controlled primarily by the strength, or chemical activity, of the base-forming elements; is dependent also on the amount of silica available in the solution; and may be modified, of course, by other factors. Thus it appears that the most active metals command the highest silicic ions, the highest silicates common in igneous rocks being the polysilicates of the alkalies, potassium and sodium—orthoclase and albite.

Further, the abundance of aluminium in most rock magmas results in the presence of abundant aluminous compounds. And this element, which is relatively inactive chemically, being found sometimes in the basic, sometimes in the acid radical, is oftenest combined with the strongest base-forming elements, potassium and sodium. These relations are illustrated by the following common, simple pyrogenetic minerals.

It is well known that the orthosilicate of sodium and aluminium (nephelite) and the metasilicate of potassium and aluminium (leucite) do not form in the presence of free silica (quartz), while metasilicates

Polysilicates	Metasilicates	Orthosilicates

$$\text{K} - \\ \text{Al} \equiv \quad (_3\text{O} \begin{array}{c}\text{N} - \\ \text{Al} \equiv\end{array} (\text{Si}_3\text{O}_8)$$
(orthoclase)   (albite)

$$\begin{array}{c}\text{K} - \\ \text{Al} \equiv\end{array} (\text{SiO}_3)_2$$
(leucite)

$$\begin{array}{c}\text{Na} - \\ \text{Al} \equiv\end{array} (\text{SiO}_4)$$
(nephelite)

$$\begin{array}{c}\text{Al} \equiv \\ \text{Ca} \overline{} (\text{SiO}_4) \\ \text{Al} \equiv (\text{SiO}_4)\end{array}$$
(anorthite)

$$\begin{array}{c}\text{Ca} \\ (\text{MgFe}) \end{array} \overline{\overline{}} (\text{SiO}_3)_2$$
(diopside)

$$\text{Si}(_8, \quad)$$

$$(\text{Mg, Fe})_2 \overline{\overline{}} (\text{SiO}_3)_2$$
(hypersthene)

$$(\text{Mg, Fe})_2 \overline{\overline{}} (\text{SiO}_4)$$
(olivine)
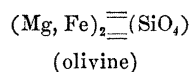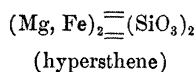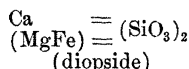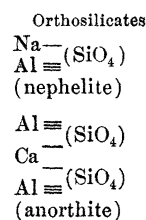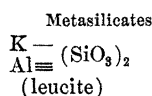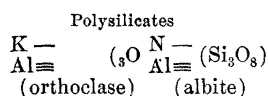
and orthosilicates of the less active metals, calcium, magnesium and iron (pyroxenes, olivine and anorthite) do. The relative chemical activity of all of the elements common to igneous rocks may be illustrated in like manner, and the probabilities of various pyrogenetic mineral compounds forming from different rock magmas may be made clear.

One of the most important factors in the discussion of the chemistry of igneous rocks is the rôle of hydrogen, whether as an active base-forming element, or as a catalytic agent, alone, as hydrogen (H), or combined with oxygen, as hydroxyl (OH). Its exact behavior in each specific case is not definitely known, but the principles applicable to several distinguishable cases are clearly established.

Adopting the idea that an acid is a hydrogen salt in which hydrogen plays the rôle of a positive, base-forming element, an acid salt may be considered as one in which all of the hydrogen has not been replaced by other base-forming metals. Such an acid salt may be looked upon as a substitution derivative from a hydrogen salt (acid), or from a normal salt by the introduction of hydrogen in place of other positive metals. An example of such a compound among pyrogenetic minerals is to be found in muscovite $(\text{K, H})\text{Al}(\text{SiO}_4)$. This might be derived from H_4SiO_4,

$\text{KAl}(\text{SiO}_4)$ or $\text{Al}_4(\text{SiO}_4)_3$. The formation of such a compound involves the presence of active hydrogen to play the rôle of metal. Muscovite is a common pyrogenetic mineral in some igneous rocks rich in silicon, with much uncombined silica, and also in others comparatively low in silica, accompanying orthosilicate and nephelite. It forms by the side of polysilicates—orthoclase and albite—and even with the disilicate, petalite. The formation of muscovite must be ascribed to the action of hydrogen upon silicon, either directly in the first instance, or, if previously formed silicates of aluminium and potassium be assumed to be the source of the compound in question, then its action in replacing part of the potassium must be that known as hydrolysis, whereby the hydrogen ions from water replace metals in the salt through a process of double decomposition.

It is known that the chemical activity of hydrogen even toward a gas, like oxygen, is greatly increased by rise of temperature; hydrogen being rather inert at ordinary temperatures. The relative activity of hydrogen and potassium toward silicon is indicated by the fact that the highest hydrogen silicate definitely known is the orthosilicate, H_4SiO_4 (orthosilicic acid), whereas potassium commonly occurs in a polysilicate, KAlSi_3O_8 (orthoclase). It has been found impossible to produce mica in open cru-

cibles from which hydrogen, or water vapor, naturally escapes at high temperatures. And muscovite is not formed pyrogenetically in surface lavas, or, if so, to a very small extent as compared with its occurrence in rocks crystallized under considerable pressure. From these facts it must be, concluded that the formation of the acid orthosilicate (muscovite) in the presence of polysilicates and free silica must be assigned to the chemical activity of hydrogen at high temperatures under sufficient pressure to hold it in the liquid magma solution.

The same argument as to the action of hydrogen in rock magmas applies to the production of the other micas, biotites and lepidolite. These compounds are complex mixed salts, and the composition of biotite involves the production of orthosilicates of magnesium and iron, which are present in biotite. These orthosilicates develop in magmas together with metasilicates of magnesium and iron—pyroxenes and hornblende—and with uncombined silica, quartz. The same compounds when alone form olivine, which generally does not develop in magmas with uncombined silica, quartz, but probably occurs with quartz oftener than has been supposed. In both of these cases the production of orthosilicate of magnesium and iron in the presence of "free" silica in magmas in which the metasilicate might be expected to form is probably due to the hydrolyzing action of water at high temperature. That is, the hydrogen at high temperature combined with some of the silicon, that otherwise would have united with magnesium and iron as metasilicate, and formed orthosilicate of these metals and orthosilicate of hydrogen.

$$(Mg, Fe)_2(SiO_3)_2 + 2H_2O \rightleftarrows$$
$$(Mg, Fe)_2(SiO_4) + H_4(SiO_4).$$
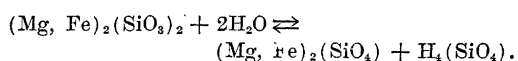
Should conditions of saturation favor the separation of the magnesium-iron compound in the solid phase, olivine would crystallize; and with falling temperature the hydrogen silicate would split up into water (H_2O) and silica (SiO_2), with the eventual crystallization of quartz.

When the amount of silica is great as compared with that of magnesium-iron orthosilicate it is possible for quartz to separate before the orthosilicate, as is the case in many hollow spherulites and lithophysæ, where fayalite, $(Fe(Mg))_2SiO_4$, is apparently almost the last mineral to crystallize, and rests upon the surface of abundant quartzes. The dependence of these forms of crystallization upon the presence of water in the magmas has been clearly demonstrated.

Other mineral compounds, whose production in igneous rocks must be referred to the hydrolyzing action of water, are amphiboles, which, as Penfield has shown, contain as an essential constituent notable amounts of hydrogen. The development of hornblende in igneous rocks appears to be dependent on conditions similar to those controlling the development of biotite, for they commonly accompany one another in rocks of intermediate composition when either is present. The particular kind of amphibole which forms in rock magmas depends primarily on the proportions of elements present, and secondarily on attendant conditions which produce variation in amphibole from one magma, which is strikingly illustrated in the two igneous rocks from Gran, Norway, described by Brögger.[2] The magmas have almost the same chemical composition, yet one crystallized into a mixture of hornblende and lime-soda-feldspar, while the other crystallized almost completely into hornblende, which contains all the components of the

[2] Brögger, W. C., "Erupt. Gest. kp. Geb.," Vol. III., 1899, p. 93, and *Quart. Jour. Geol. Soc.*, Vol. L., 1894, p. 19.

feldspar and hornblende in the first-mentioned rock.

That hornblendes are less stable compounds in igneous magmas than pyroxenes and numerous other minerals, is shown by the frequent occurrence of paramorphs of other minerals after hornblende, commonly seen in so-called black borders, and the absence of correspondingly changed crystals of other minerals.

Another chemical principle involved in the production of pyrogenetic minerals is that affecting the formation of compounds that possess common ions when in solution. It is known that when there are in a solution ions capable of entering two or more compounds, the concentration of the least soluble compound may be increased by the entrance of ions derived from other compounds into its molecules. And this may proceed to the complete incorporation of the common ions within one compound upon its separation in the solid phase. This has sometimes been called erroneously "mass action." That compound forms at the expense of another in any particular instance which is the more stable under attendant conditions. Illustrations of this action are found: in the case of the complex amphibole in the hornblendite of Gran already mentioned; in aluminous pyroxenes (augites), which contain components capable of forming lime-soda-feldspars, as pointed out by Pirsson, and in numerous other rock minerals. This principle is probably concerned in the production of the lime-soda-feldspars with notable amounts of albite molecules, as in andesine and labradorite, in magmas so low in silica as to necessitate the production of leucite from the potassium present, when the more active potassium should have combined with the silicon in a polysilicate (orthoclase), leaving the less active sodium to enter orthosilicate (nephelite).

Following out the discussion of all the probable compounds likely to form under known chemical laws from molten rock magmas upon cooling, and taking into consideration the relative chemical activities of the several constituent elements in igneous rocks, it is possible to deduce a probable mineral composition for any given magma, under given conditions of cooling. The mineral composition of igneous rocks then becomes a necessary consequence of the chemical reactions likely to obtain in molten rock magmas, and depends not only on the kinds and amounts of the elements present in each case, but also on the conditions of temperature and pressure modifying the chemical activities of the elements and the stability of the compounds. As these conditions are known to vary with the experience of different magmas during eruption and solidification, the minerals produced in chemically similar magmas are not to be expected to be always alike, and the variations in composition are in this way understood.

Having considered the possible chemical reactions that may give rise to mineral compounds in rock magmas, the next step in the treatment of the subject is a discussion of the process and results of separation of various compounds or substances from magma solutions upon change of physical conditions attending the eruption of magmas. These may separate as gases, liquids or solids, chiefly as solids. But gases escape in large volumes upon the eruption of lavas, mostly as water vapor. There are other kinds in smaller, though often in considerable, amounts. The effects of this loss of gases are in the chemical composition of the rock magma, in the concentration of the remaining substances, and in the viscosity of the magma, which may increase notably upon loss of gas.

Liquids, probably, do not separate as such from molten magmas to any consider-

able extent. Apparently liquid silicates are miscible in one another in all proportions, though suggestions that they may not be have been advanced by some petrologists. It is known that liquid sulphides and silicates are not miscible in all proportions at all temperatures. And where sulphides exist in large amounts, separation in the liquid phase may take place with falling temperature.

Separation of solids from solution depends upon the attainment of a sufficient molecular concentration of substances to saturate the solution. Saturation may be brought about in several ways: by chemical reaction within the solution consequent upon a change of chemical equilibrium; by change of temperature, usually by lowering temperature; by change of pressure, either acting in an opposite manner from temperature or by affecting the gas content.

Solids may separate when the point of saturation for them has been reached, or the liquid may become superheated, and separation be delayed. In this condition separation is often induced by the insertion of a solid of like composition, or of an isomorphous compound, or by agitating. Such a condition of a liquid has been called *metastable,* and in this condition, as shown by Miers in laboratory observations on liquids of organic compounds, crystallization of the separating substance takes place, at relatively few points, and proceeds gradually, according to degree of concentration and other factors, until comparatively large individuals are formed. If supersaturation proceeds without separation of solid phase a point will be reached when separation will take place spontaneously at many points in the liquid and continue rapidly. This is the *labile* condition of the liquid. When this condition is reached by a cooling liquid crystallization often takes place suddenly as a shower of minute individuals, as observed by Miers. The bearing of these facts on the textures of igneous rocks is apparent, and a knowledge of the laws relating to the separation of solids from liquids; the order in which those of different substances may follow one another in a mixed solution; the separation of isomorphous compounds; and the shapes that may be assumed by the resulting crystals of various minerals lead to an understanding of the texture of igneous rocks.

A supersaturated condition is more readily obtained in more viscous liquids, which are more apt to solidify without crystallization, as glasses, than more fluid liquids. The most familiar illustrations of this law among igneous rocks are the persilicic (rhyolitic) lavas, which often form glasses (obsidians). The question has been raised by Crosby, and others, whether an earthquake happening when a magma was in a sufficiently supersaturated, metastable, condition might not induce crystallization of some of the constituent compounds.

Crystallization may begin with different degrees of supersaturation of the liquid, and would proceed at different rates according to the degree of supersaturation, being more rapid the greater the concentration. It would also be more rapid the greater the molecular diffusivity, that is, the lower the viscosity of the liquid, and the greater the rate of cooling, so long as this does not increase viscosity too rapidly. Gradual or slow crystallization at comparatively few centers would yield relatively few, large, crystals; whereas sudden, rapid crystallization from many centers would produce many small ones.

High fluidity in solutions would permit easy diffusion of separating molecules toward crystallizing centers, favoring the growth of relatively large individuals. High viscosity would retard diffusion and

favor the growth of many small crystals. This is well illustrated by the laboratory experience of Day with the crystallization of various lime-soda-feldspars. Thus it was found that 100 grams of liquid anorthite crystallized completely in ten minutes to fair-sized crystals, and it required quick chilling to prevent its crystallization and to produce glass. A mixture of equal parts of anorthite and albite (Ab_1An_1) required a gradual cooling extending over several days to effect complete crystallization, whereas liquid albite could not be induced to crystallize through days of cooling in an open crucible. Comparing the size of the crystals of anorthite produced in 10 minutes with those of oligoclase-andesine (Ab_3An_1) which were produced by gradual cooling through two days, the former were from 3 to 5 mm. thick, the latter about 0.005 mm. thick. That is, the more liquid anorthite produced crystals one thousand times as thick in about one three-hundredth the time, a ratio of 300,000 : 1.

The rate of separation of solid from liquid also depends on the solubility and the amount of any substance in solution. The greater each of these factors the more rapid the rate of crystallization and the larger the crystals, other things being constant in compared cases. This law has been expressed definitely by von Pickardt as follows: "The velocity of crystallization (separation in solid phase) is diminished by the addition of foreign substances to the liquid phase of a substance, the diminution of the velocity being the same for equimolecular quantities of all substances."

The order of succession in the separation of different kinds of minerals from molten magma is a subject upon which there has been some difference of opinion among petrologists. It has been clearly demonstrated that the order is not an invariable one. The laws relating to the order of separation of solids from mixed solutions have been definitely determined for solutions of various compounds in one another and the general principles are applicable to the study of igneous rocks. The attention of petrographers has been called to these laws by Vogt.

The order of separation of several compounds in solution in one another depends on the degree of saturation of each, that with the highest degree of saturation, or that one whose saturation point is reached first upon the cooling of the solution separates first. The relation between saturation, molecular concentration and the melting point of each compound has been established in general terms for different sets of cases by Meyerhoffer, and further elaborated by Roozeboom for cases of crystals of isomorphous compounds.

In all cases where the mixed compounds do not unite chemically to form new compounds, or physically as mixed crystals, there is one minimum point of temperature for a mixture of two compounds, and more than one in more complex mixtures, at which a certain proportioned mixture remains liquid. At this temperature the two components of a binary mixture will crystallize simultaneously. This minimum temperature and particular mixture are called eutectic.

Miers has shown that when supersaturation sets in and the labile condition is taken into account, the minimum temperature of separation and corresponding proportions of the mixture do not coincide with those already described as eutectic. These he has called hypertectic.

A study of these principles shows that there can be no invariable order of separation, or crystallization, of the constituent compounds in a series of mixed solutions composed of like compounds. And that simultaneous crystallization of pairs, or of

more than two kinds of separating compounds, may take place in solutions of whatever composition. Eutectic mixtures may consist of more than two components. Moreover, the supersaturation of a solution by one component may affect the proportion between two or more components at the moment of synchronous crystallization. Synchronously crystallized mixtures of certain kinds of components, therefore, are not necessarily similarly proportioned. The bearing of these principles on the crystallization and texture of igneous rocks is manifold. A few illustrations will suffice. Quartz may be the first mineral to separate from a molten magma when the solution is so rich in silica that upon cooling it becomes saturated with silica before being saturated with feldspar or some ferromagnesian compound, or even iron oxide. Quartz may be the last mineral to separate from magmas so rich in feldspar or ferromagnesian compounds as to become saturated by these upon cooling before being saturated with quartz.

Either labradorite or augite may separate first from a mixture of the two, according to which saturates the solution first upon cooling, and this depends on their relative amounts in the solution, and their order of crystallization is further modified by the possibility of one or the other producing supersaturation in the liquid. This will account for the differences of texture often noted in certain gabbros, or basalts, of almost the same composition.

Eutectic mixtures, or those whose components crystallize simultaneously, often yield aggregates of intergrown crystals, the most familiar examples of which are found in graphic granite, and certain alloys. But Miers has called attention to the fact that the simultaneous crystallization of two compounds in eutectic proportions does not invariably produce intergrown individual crystals, or graphic intergrowths. It may result in granular aggregations of concerted, adjacent anhedrons not intergrown, which corresponds to observations on the textures of igneous rocks, for many rocks of like composition in some instances exhibit graphic texture, in others evenly granular texture. Accepting graphic intergrowth as evidence of synchronous crystallization, and of the existence of eutectic proportions in some cases between the several mineral compounds at the moment of crystallization, it is to be noted that such intergrowths have been developed in igneous rocks between quartz and potash-feldspar, quartz and sodic feldspars, quartz and biotite, feldspar and pyroxene, feldspar and hornblende, feldspar and nephelite, pyroxene and iron oxide (probably magnetite) and between other pairs of minerals.

The separation of solids, that is, the crystallization of minerals from rock magmas, must be an extremely intricate process, because of the complex character of the solution, the variable and irregular changes in temperature and pressure consequent on the movements of eruption, the variations in composition due to changes in gaseous components, and the possibility of chemical reaction among the components with changes of chemical equilibria, as well as the probable supersaturation of the magma by different components to various degrees. This complexity will doubtless prevent exact statements of the relations between composition and texture, but approximations may be made to the proper explanation of some of the most common and characteristic textures, which will render them more intelligible to the student.

The crystallization of a substance from solution involves molecular diffusion, and molecular orientation, and these are functions of molecular attraction, composition of the molecular compound, viscosity of the

liquid, composition of the liquid, temperature, pressure and time, or rate of changing conditions. The combination of these factors in the case of any cooling rock magma results in rock possessing a certain degree of crystallinity, which may range from a state of complete crystallinity, to the reverse, or complete glassiness. When more or less crystalline, the size of the crystals becomes a feature of consequence. The granularity, or the size of crystals in rocks, has been given a prominent rôle in most descriptions, and classifications of rocks. The shapes of individual crystals clearly give distinctive character to the pattern, or fabric, of rocks, and shape is largely a function of crystal structure and physical habit of specific minerals. The recognition of these relationships and their systematic treatment in the description and discussion of igneous rocks will lift the subject out of a maze of confusing, complex detail, usually treated in an uncoordinated and meaningless manner.

Application of principles of molecular diffusion; of laws relating to solution pressure, or osmotic pressure; of conditions controlling crystallization, or the separation of solids from solutions; of conditions affecting the physical character of liquids, or rock magmas; to the observed variability in the composition of igneous rocks, and to the known relation between their composition, order of eruption, and mode of occurrence, leads to conceptions of their origin from other magmas, by processes called by the general designation of *differentiation.*

With such an understanding of the causes of heterogeneity in rock solutions the great variability in the composition of igneous rocks as shown by chemical analyses, and by a quantitative study of their mineral composition, appears as the natural, as well as the logical, result of their mode of formation.

Mineralogical and constitutional facies of igneous rocks are readily comprehended; and the absence of fixed types of magmas, or of frequently recurring bodies of igneous rocks with definite or invariable composition, becomes "natural," and is the thing to be expected. Variations in texture within one rock mass, and among rock bodies having various modes of occurrence, are readily understood as the results of variability in the conditions attending volcanic eruption.

As to the possible character of volcanic eruption, some conception of it may be derived from a consideration of the probable condition of highly heated rock material under great pressure deep beneath the surface of the earth, as well as its probable experience in moving upward and out upon the earth's surface.

The high temperature of volcanic lavas when they reach the atmosphere, the fact that they were losing heat continually from the time of their first movement upward, the evidence that they were completely liquid at some stage in their eruption, together with the observed gradient of increase of temperature downward from the surface of the earth, all combine to show that rock magmas come from some region where the temperature is considerably above the melting point of igneous rocks. The behavior of the earth as a rigid globe, and the known effect of pressure in counteracting that of heat, together with its estimated high gradient of increase downward within the earth, force the conclusion that at sufficient depth magma, though hot enough to be liquid, behaves as a solid. Such conditions of heat and pressure can not vary abruptly from place to place, but must be nearly the same for large volumes of material; and differences of temperature and pressure must obtain very gradually, chiefly in vertical directions. Magma in

such a position must be in a virtually static condition until it experiences change of pressure or stress. Whatever its composition, it must remain unchanged.

A change of stress may come about by movement in the overlying portion of the earth. Orogenic movement, readjustment of the upper rigid, rock mass, from whatever causes, when profound, must affect the stresses in still deeper parts. The known crustal movements behave as bendings of the upper rock mass, which in places at the earth's surface appear to result in tensile stresses; in places, in compressional stresses. Beneath each of these the effective stresses must be of the opposite kind; under the tensile, compressive stresses, and under the upper compressive ones, tensile stresses. Tensile stresses should occur at some distance below ocean beds, and more especially along the borders of oceans and continents. Compressive stresses should occur, in general, beneath continental masses.

Tensile stress, as at the bottom of a synclinal arch, operating in a rigid mass must communicate itself downward as far as the mass behaves rigidly. When the hot mass is potentially fluid, that is, is kept solid by pressure, change of stress must be followed by change of position of the mass. A tendency to pull apart or stretch in the potentially fluid mass must be followed by a yielding of the mass. At a point sufficiently cool for the mass to act as a solid a tendency to fracture and to open a fissure would be followed by a movement of the slightly more heated mass beneath to occupy the space between the fractured solid; these differences of temperature and of rigidity are to be understood in a mathematical sense as differential, there being a gradation of physical conditions between adjacent parts of the mass. There will be no open space, or fissure, in the ordinary

sense. But it must be understood that at whatever depth the mass may be considered solid, there it may fracture, part and become the walls of a layer or body of intruded liquid, provided the liquid have nearly the same density as the solid mass.

The statement made by Van Hise and Hoskins that open cracks, or fissures, can not exist at greater depths than about 10,000 meters was made on the assumption that the filling is water; the difference in weight of the rock and the hydrostatic pressure of the corresponding column of water being compared with the crushing strength of the solid rock. When the liquid is heavier than water the same method of calculation allows fissures filled with such liquid to exist at greater depths; and if the weight of the column of liquid equals that of the wall rock, the two will remain in equilibrium at any depth. Consequently at any depth in the earth mass where a tendency to part may exist, hotter and potentially more fluid material beneath may move up and permit the parting of the slightly more rigid mass to take place. This would appear to be the initial step in the eruption of rock magma.

As the mass shifts its position upward the pressure upon it decreases, resulting in some expansion of the volume, some decrease in density, some increase in mobility. And the rising mass is hotter than the masses between which it is rising, unless movement is at the same rate as the diffusion of heat. In proportion as the tensile stress is strong the upward movement will be pronounced, and may result in a flow of very dense, hot, viscous magma toward the surface of the earth. The greater the vertical distance traversed and the more rapid the rate of movement, the greater the difference in temperature between the magma and the enclosing mass.

That the eruption of rock magma is con-

sequent upon the adjustment of accumulated stresses within the overlying rocks is indicated by the sequence of fractures and lava flows in the uppermost parts of the earth, and the opening of eras of great volcanic activity after profound orogenic movements have disturbed the comparatively quiet action of forces that have been gradually shifting the stresses within the outer portion of the earth. The magnitude of the adjusting action is evinced by the extent of territory simultaneously affected. As, for example, the initiation of volcanic action on a gigantic scale throughout western America at the end of Cretaceous time, after an enormous period of nearly uniform conditions of comparative quiet.

The eruptive impulse, or energy, causing the upward flow of magma, must originate in the expansion of the magma upon relief of pressure consequent upon the adjustment of stresses in the overlying mass, and from expansive energy of dissolved gases. That the eruptive force is of nearly the same order of magnitude as the stresses within the earth's crust is shown by the relatively small amount of material erupted upon the surface of the earth compared with the bulk of the whole; by the common intrusion of magma along fracture planes and along those of structural weakness, rather than at random through rock masses; and most conspicuously, by the evidence of equilibrium with the atmosphere maintained by lava in volcanic craters. Open vents are known to exist for centuries without great extrusion of rock magma, as at Stromboli. The stresses which produce condensation of volume in proportion to depth and the results of expansion of volume are, therefore, somewhat evenly balanced.

The effect of expanding gases is shown in the explosive character of many eruptions, and the periodic character of all eruptions from open vents (volcanoes). It must increase the volume of all magmas as pressure is relieved. Its effectiveness must increase in proportion to the amount of gas in the magma, which may result from diffusion of gas from greater depths of magma, and also from accession from adjacent rocks under favorable conditions.

Spasmodic eruption may follow sudden yielding of overlying rocks to long continued stresses, as in the case of massive, or fissure, eruptions when there may have been no considerable explosive action of gas; or it may result from an accumulation of gas pressure sufficient to rupture overlying rock masses. Eruption is then accompanied by abundant evidence of explosion. Both causes undoubtedly operate together in most cases.

In so far as magmatic eruption is a result of volumetric expansion of the magma, due to relief of pressure, the shrinkage of volume due to cooling will retard eruption, or eventually stop it. Crystallization will operate in the same direction. In proportion as eruption is due to expansion of dissolved gas, the escape of gas from magma, or the reduction of supply, will lessen the force of eruption, or eventually put an end to it. The supply of gas from great depths may be reduced by the gradual diffusion of whatever is in a position to be appreciably diffused; or the supply from rocks adjacent to intruded magma may be cut off by the closing of pores in these rocks through metamorphism; porous rocks becoming dense and almost impervious to gases. In these ways eruptive action initiated by crustal readjustment after continuing for variable periods may come to an end. Readjustment of stresses may recur from time to time in any region, either at such widely remote periods that the volcanic activities associated with each readjustment constitute distinct and separate periods of action; or at such frequent intervals that the results of several profound movements are combined to form a

prolonged period of complex volcanic eruptions.

Independence of action at neighboring volcanoes, either as to period of eruption, volume of magma erupted, explosive or quiet character of action, or relative height of lava column in conduit of volcanoes, follows from local variation in the factors entering into the process of magma eruption, such as, the volume of magma involved in each conduit extending to profound depths, the shape of the conduit, the temperature of the magma; the rate of cooling; the amount of gas diffused in any given time; the character of the surrounding rocks; and the stability of the surrounding rock masses as a complex whole. The chemical composition of the magma is also a factor involved in the activity of a particular volcano. But the composition of the magma is also a feature by which volcanoes may show independence. Differences in the composition of rocks in neighboring volcanoes is to be sought in variation in the differentiation of magmas during the course of eruption from deepseated to surficial positions.

Among the results of such differentiation may be mentioned the production of complementary rocks, which may occur in rock bodies of various forms. A special case of local differentiation, usually associated immediately with crystallization and solidification of parts of a magma, is the production of contemporaneous veins and pegmatites. When complementary rock magmas are erupted so close to one another in space and time that they come in conjunction while still highly heated, they may diffuse into one another, or blende to such an extent as to yield hybrid rocks, or mixed dikes, sheets, etc., as observed by Harker on the Isle of Skye.

The eruption of rock magmas through solid rocks and their solidification in various positions within or upon other rocks condition the modes of occurrence of igneous rocks, as those of lava streams, dikes, sheets, laccoliths, etc. And the parting or cracking of the solid rock, upon cooling, or its arrangement after fragmentation in various ways leads to distinctive structures, such as columnar, spheroidal or brecciated.

Having acquired a knowledge of the general principles applicable to all igneous rocks, it is in order to consider more specifically those occurring in all known parts of the world: first, systematically, according to some comprehensive scheme of arrangement, or classification, and then according to the groups, or associations, in which they occur in various regions, that is, according to petrographical provinces, or co-magmatic regions.

In order to describe many rocks a nomenclature is necessary, and the confusion existing in that in present use is best understood by considering the history of the growth of petrography, and the changes that have gone on in the definition and use of the oldest and commonest rock names, and descriptive terms. With this review should be associated a sketch of the development of rock classification, which has been furnished to the student in an interesting form by Cross.

A successful treatment of the subject of igneous rocks along the lines indicated would go far toward the removal of petrology from a state of distracting empiricism, and the placing of it on a more rational foundation.   JOSEPH P. IDDINGS

WASHINGTON, D. C.

CONDUCT OF SCIENTIFIC WORK UNDER
THE UNITED STATES GOVERNMENT[1]

To the Senate and House of Representatives:

In compliance with the provisions of section 8 of the act of Congress making appropriations

[1] Message from the President of the United States, transmitting a report of the National Academy of Sciences relating to the conduct of the scientific work under the United States government.